Chapter 1
Biochemistry and the Organization of Cells

SUMMARY
Section 1.1

- Biochemistry describes the molecular nature of life processes. In living cells, many chemical reactions take place simultaneously.
- Cells of all types have so many fundamental features in common that it is reasonable to say that they all had a common origin.

Section 1.2
- Life is based on compounds of carbon. This is the subject matter of organic chemistry.
- The reactions of organic compounds are those of their functional groups, which are specifically linked atoms that react in similar ways under many different conditions.

Section 1.3
- Our solar system, including the Earth, is postulated to have been formed from chemical elements produced by first-generation stars. The early Earth had an atmosphere that consisted of simple chemical compounds.
- The atmospheric conditions of the early Earth allowed the formation of molecules, such as amino acids, that play a role in life processes.
- Several theories describe the origin of living cells from component molecules. All require explanations for coding and for catalytic activity, and all assign an important role to RNA.

Section 1.4
- All cells contain DNA and are separated from their environment by a cell membrane. Prokaryotic cells do not have significant internal membranes, but the larger cells of eukaryotes have an extensive membrane system. The internal membranes mark off the organelles, portions of the cell with a specific function.

Section 1.5
- Prokaryotes have a nuclear region, which contains DNA, and ribosomes, the site of protein synthesis, as their main features. They have a cell membrane, but do not have an internal membrane system.

Section 1.6
- Three of the most important organelles in eukaryotic cells are the nucleus, the mitochondrion, and the chloroplast. Each is separated from the rest of the cell by a double membrane. The nucleus contains most of the DNA of the cell and is the site of RNA synthesis. The mitochondria contain enzymes that catalyze important energy-yielding reactions. Chloroplasts, which are found in green plants and

green algae, are the sites of photosynthesis. Both mitochondria and chloroplasts contain DNA that differs from that found in the nucleus, and both carry out transcription and protein synthesis distinct from that directed by the nucleus.
- Other organelles play specific roles. They include the Golgi apparatus, lysosomes, and peroxisomes.

Section 1.7
- In the five-kingdom classification scheme, prokaryotes have a kingdom to themselves (Monera). The remaining four kingdoms – protists, fungi, plants, and animals – consist of eukaryotes.
- In the three-domain classification schemes, eukaryotes have a domain to themselves. Two domains consist of prokaryotes. Eubacteria are the commonly encountered prokaryotes. Archaea are organisms that live in extreme environments such as those that were found on the early Earth.
- Many theories about the rise of eukaryotes from prokaryotes focus on a possible role for symbiosis.
- The idea of endosymbiosis, in which a larger cell engulfs a smaller one, plays a large role in scenarios for the development of organelles in eukaryotic cells.

Section 1.8
- The sun is the source of energy for all life on Earth. It provides the energy for photosynthesis, which produces carbohydrates as well as oxygen. Carbohydrates can be processed in chemical reactions that release energy.
- Reactions that release energy are favored and thus are likely to occur. Thermodynamics is the branch of science that predicts the likelihood of reactions.

Section 1.9
- A spontaneous reaction is one that will take place without outside intervention. This point does not specify reaction rate. Some spontaneous processes can take a long time to occur.

Section 1.10
- The change in free energy (ΔG) that accompanies a reaction determines whether that reaction is spontaneous at a given temperature and pressure.
- A negative free energy change ($\Delta G<0$) is characteristic of a spontaneous reaction. A positive free energy change ($\Delta G>0$) indicates that the reaction is not spontaneous, but the reverse process is spontaneous. When the free energy change is zero ($\Delta G = 0$), the reaction is at equilibrium.

Section 1.11
- Living things are ordered assemblies of molecules. They represent a local decrease in entropy. Because the entropy of the universe increases in spontaneous processes, this local decrease in entropy is offset by a larger increase in the entropy of the surroundings. There is an increase in total entropy.

LECTURE NOTES

As an introduction, this should not take more than one lecture. Students should be made aware of some unifying themes and background information. Biochemistry is intimately related to other physical sciences, most especially organic chemistry. Living things may be seen as hierarchical structures, and as such, the properties of functional groups on molecules lead, ultimately, to the complexity of cells and multicellular organisms. A very brief introduction to thermodynamics is included here as well.

LECTURE OUTLINE

I. Basic Themes
- A. Interconnections among physical sciences
- B. Structural hierarchy in living systems
- C. Review of functional groups in biomolecules

II. Origins of life
- A. Big Bang — Elements, comparison of abundances in living organisms vs. universe at large
- B. Origin of biomolecules, abiotic synthesis
- C. Polymeric structure of biomolecules
- D. Molecules to cells
    1. Importance of catalysts
    2. RNA world and other theories

III. Prokaryotes vs. eukaryotes – structural comparisons
- A. Prokaryotes
    1. No membrane-bound nuclei, but a nuclear region
    2. Ribosomes – protein synthesis
    3. Cell membrane
    4. Cell wall
- B. Eukaryotes
    1. Many membrane-bound organelles
    2. Structures and functions: nucleus, mitochondria, ER (+/- ribosomes), chloroplasts, Golgi, lysosomes, peroxisomes, cytoskeleton, vacuoles

IV. Biological classification systems
- A. Five kingdoms
    1. Fungi, plants, animals – mostly multicellular, all eukaryotes
    2. Protists – mostly unicellular, all eukaryotes
    3. Monera – prokaryotes
- B. Three domains
    1. Archaebacteria
    2. Eubacteria
    3. Eukarya
- C. Endosymbiotic theory

V. Energy Use
  A. Sun as ultimate source
  B. Thermodynamics, favorability of processes, release of energy

ANSWERS TO PROBLEMS

1.1 Basic Themes

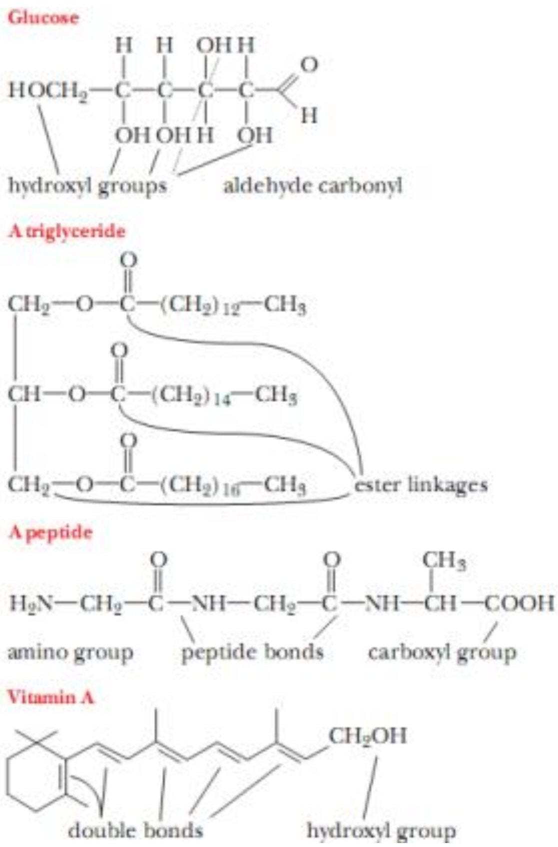
1. A polymer is a very large molecule formed by linking smaller units (monomers) together. A protein is a polymer formed by linking amino acids together. A nucleic acid is a polymer formed by linking nucleotides together. Catalysis is the process that increases the rate of chemical reactions compared with the rate of the uncatalyzed reaction. Biological catalysts are proteins in almost all cases; the only exceptions are a few types of RNA, which can catalyze some of the reactions of their own metabolism. The genetic code is the means by which the information for the structure and function of all living things is passed from one generation to the next. The sequence of purines and pyrimidines in DNA carries the genetic code. (RNA is the coding material in some viruses).

1.2 Chemical Foundations of Biochemistry

2. The correct match of functional groups and the compounds containing those functional groups is given in the following list:

Amino group	$CH_3CH_2NH_2$
Carbonyl group (ketone)	CH_3COCH_3
Hydroxyl group	CH_3OH
Carboxyl group	CH_3COOH
Carbonyl group (aldehyde)	CH_3CH_2CHO
Thiol group	CH_3SH
Ester linkage	$CH_3COOCH_2CH_3$
Double bond	$CH_3CH{=}CHCH_3$
Amide linkage	$CH_3CON(CH_3)_2$
Ether	$CH_3CH_2OCH_2CH_3$

3. The functional groups in the compounds follow:



4. Before 1828, the concept of vitalism held that organic compounds could be made only by living systems and were beyond the realm of laboratory investigations. Wöhler's synthesis showed that organic compounds, like inorganic ones, did not require a vitalistic explanation, but that, rather, they obeyed the laws of chemistry and physics and thus were subject to laboratory investigation. Subsequently, the concept was extended to the much more complex, but still testable, discipline of biochemistry.

5. Urea, like all organic compounds, has the same molecular structure, whether it is produced by a living organism or not.

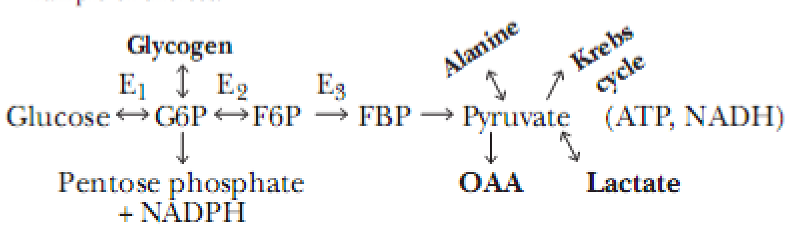
6.

Item	Organic	Biochemical
Solvent	Varies (smelly)	Water (usually)
Concentrations	High	Low (mM, μM, nM)
Use catalyst?	Usually not	Almost always (enzymes)
Speed	Min, hr, day	μsec, nsec
Temp	Varies (high)	Isothermal, ambient temp
Yield	Poor–good (90%)	High (can be 100%)
Side reactions	Often*	No
Internal control	Little	Very high**—choices
Polymers (product)	Usually not	Commonly (proteins, nucleic acids, saccharides)
Bond strength	High (covalent)	High, weak (in polymers)
Bond distances	Not critical	Critical (close fit)
Compartmented	No	Yes (esp. eukaryotes)
Emphasis	One reaction	Pathways, interconnected (control** choices)†
System	Closed or open	Open (overcome $+\Delta G$)

* Example of side reactions: Glucose → G6P *or* G1P *or* G2P.

** Control levels: enzyme, hormone, gene.

† Example of choices:



1.3 The Beginnings of Biology: Origin of Life

7. It is generally believed that carbon is the likely basis for all life forms, terrestrial or extraterrestrial.

8. Eighteen residues would give 20^{18} possibilities, or 2.6×10^{23} possibilities. Thus, 19 residues would be necessary to have at least Avogadro's number (6.022×10^{23} of possibilities

9. The number is 4^{40} or 1.2×10^{24}, which is twice Avogadro's number.

10. RNA is capable of both coding and catalysis.

11. Catalysis allows living organisms to carry out chemical reactions much more efficiently than without catalysts.

12. Two of the most obvious advantages are speed and specificity; they also work at constant temperature or produce little heat.

13. Coding allows for reproduction of cells.

14. With respect to coding, RNA-type polynucleotides have been produced from

monomers in the absence of either a preexisting RNA to be copied or an enzyme to catalyze the process. The observation that some existing RNA molecules can catalyze their own processing suggests a role for RNA in catalysis. With this dual role, RNA may have been the original informational macromolecule in the origin of life.

15. It is unlikely that cells could have arisen as bare cytoplasm without a plasma membrane. The presence of the membrane protects cellular components from the environment and prevents them from diffusing away from each other. The molecules within a cell can react more easily if they are closer to each other.

1.4 The Biggest Biological Distinction—Prokaryotes and Eukaryotes

16. Five differences between prokaryotes and eukaryotes are as follows: (1) Prokaryotes do not have a well-defined nucleus, but eukaryotes have a nucleus marked off from the rest of the cell by a double membrane. (2) Prokaryotes have only a plasma (cell) membrane; eukaryotes have an extensive internal membrane system. (3) Eukaryotic cells contain membrane-bounded organelles, while prokaryotic cells do not. (4) Eukaryotic cells are normally larger than those of prokaryotes. (5) Prokaryotes are single celled organisms, while eukaryotes can be either single-celled or multicellular.

17. Protein synthesis takes place on ribosomes both in prokaryotes and in eukaryotes. In eukaryotes, ribosomes may be bound to the endoplasmic reticulum or found free in the cytoplasm; in prokaryotes, ribosomes are only found free in the cytoplasm.

1.5 Prokaryotic Cells

18. It is unlikely that mitochondria would be found in bacteria. These eukaryotic organelles are enclosed by a double membrane, and bacteria do not have an internal membrane system. The mitochondria found in eukaryotic cells are about the same size as most bacteria.

1.6 Eukaryotic Cells

19. See Section 1.6 for the functions of the parts of an animal cell, which are shown in Figure 1.10a.

20. See Section 1.6 for the functions of the parts of a plant cell, which are shown in Figure 1.10b.

21. In green plants photosynthesis takes place in the membrane system of chloroplasts, which are large membrane-enclosed organelles. Photosynthetic bacteria have extensions of the plasma membrane into the interior of the cell called chromatophores, which are the sites of photosynthesis.

22. Nuclei, mitochondria, and chloroplasts are all enclosed by a double membrane.

23. Nuclei, mitochondria, and chloroplasts all contain DNA. The DNA found in mitochondria and in chloroplasts differs from that found in the nucleus.

24. Mitochondria carry out a high percentage of the oxidation (energy-releasing) reactions of the cell. They are the primary sites of ATP synthesis.

25. The Golgi apparatus is involved in binding carbohydrates to proteins and in exporting substances from the cell. Lysosomes contain hydrolytic enzymes,

peroxisomes contain catalase (needed for the metabolism of peroxides), and glyoxysomes contain enzymes needed by plants for the glyoxylate cycle. All of these organelles have the appearance of flattened sacs, and each is enclosed by a single membrane.

1.7 How We Classify Eukaryotes and Prokaryotes

26. Monera includes bacteria (e.g., E. coli) and cyanobacteria. Protista includes such organisms as Euglena, Volvox, Amoeba, and Paramecium.
27. The kingdom Monera consists of prokaryotes. Each of the other four kingdoms consists of eukaryotes. Fungi includes molds and mushrooms. Plantae includes club mosses and oak trees. Animalia includes spiders, earthworms, salmon, rattlesnakes, robins, and dogs.
28. The five-kingdom classification takes into account the fact that bacteria, fungi, and protists do not fit the plant/animal divide.
29. The major advantage of being eukaryotic is that of having compartments (organelles) with specialized functions (and thus division of labor). Another advantage is that cells can be much larger without surface area–to–volume considerations being critical because of compartmentalization.
30. See the discussion of the endosymbiotic theory in Section 1.7.
31. See Question 30. The division of labor in cells gives rise to greater efficiency and a larger number of individuals. This in turn allows more opportunity for evolution and speciation.

1.8 Biochemical Energetics

32. Processes that release energy are favored.

1.9 Energy and Change

33. The term spontaneous means energetically favored. It does not necessarily mean fast.

1.10 Spontaneity in Biochemical Reactions

34. The system consists of the nonpolar solute and water, which become more disordered when a solution is formed; ΔS_{sys} is positive but comparatively small. ΔS_{surr} is negative and comparatively large because it is a reflection of the unfavorable enthalpy change for forming the solution (ΔH_{sys}).
35. Processes (a) and (b) are spontaneous, whereas processes (c) and (d) are not. The spontaneous processes represent an increase in disorder (increase in the entropy of the Universe) and have a negative $\Delta G°$ at constant temperature and pressure, while the opposite is true of the nonspontaneous processes.
36. In all cases, there is an increase in entropy, and the final state has more possible random arrangements than the initial state.
37. Since the equation involves multiplication of ΔS by T, the value of ΔG is temperature-dependent.
38. If one considers entropy a measure of dispersion of energy, then at higher temperatures, it is logical that molecules would have more possible arrangements due to increased molecular motion.

39. Assuming the value of ΔS is positive, an increase in temperature increases the $-\Delta G$ contribution of the entropy component to the overall energy change.
40. The heat exchange, getting colder, reflects only the enthalpy or ΔH component of the total energy change. The entropy change must be high enough to offset the enthalpy component and to add up to an overall $-\Delta G$.
41. Entropy would increase. Two molecules, ADP and P_i, can be randomized in more ways than a single molecule, ATP, can.

1.11 Life and Thermodynamics

42. The lowering of entropy needed to give rise to organelles leads to higher entropy in the surroundings, thus increasing the entropy of the Universe as a whole.
43. Compartmentalization in organelles brings components of reactions into proximity with one another. The energy change of the reaction is not affected, but the availability of components allows it to proceed more readily.
44. DNA would have higher entropy with the strands separated. There are two single strands instead of one double strand, and the single strands have more conformational mobility.
45. See the answer to Question 43. It is still unlikely that cells could have arisen as bare cytoplasm, but the question of proximity of reactants is more to the point here than the energy change of a given reaction.
46. It would be unlikely that cells of the kind we know would have evolved on a gas giant. The lack of solids and liquids on which aggregates could form would make a large difference.
47. The available materials differ from those that would have been found on Earth, and conditions of temperature and pressure are very different.
48. Mars, because of conditions more like those on Earth.
49. A number of energetically favorable interactions drive the process of protein folding, ultimately increasing the entropy of the Universe.
50. Photosynthesis is endergonic, requiring light energy from the Sun. The complete aerobic oxidation of glucose is exergonic and is a source of energy for many organisms, including humans. It would be reasonable to expect the two processes to take place differently in order to provide energy for the endergonic one.